COMPARISON OF US AND FRENCH RATIONAL PROCEDURES FOR THE DESIGN OF FLEXIBLE AIRFIELD PAVEMENTS

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ABSTRACT

In the US, FAARFIELD is now the new standard Federal Aviation Administration (FAA) design software for airfield pavements. In France, the *Alizé*-Airfield pavement program, developed by the Laboratoire Central des Ponts et Chaussées (LCPC) under a cooperative agreement with the Service Technique de l'Aviation Civile (STAC), is intended to become the reference design software. A similar rational approach to design is used in these two programs. It consists in comparing computed strains induced by traffic loads at critical levels of the designed structure to allowable strains.

This paper deals with the comparison of US and French procedures for the design of flexible airfield pavements. It is aimed at describing the specifics of each of the two computer programs (e.g., model hypotheses, probability considerations, use of conservative parameters). A sensitivity study is conducted so as to quantify the change in output data with respect to the change in input parameters in both software programs. The versions used for comparison are FAARFIELD version 1.302 and *Alizé*-Airfield pavement 4.1.0. This parametric study concerns the influence of various input parameters (subgrade and asphalt moduli, gross weight, number of passes, layer thicknesses) on flexible thickness design for both isolated aircraft and traffic mixes, and considering both asphalt and subgrade failure criteria. A comparison of computed mechanical values obtained from FAARFIELD output files and *Alizé*-Airfield pavement charts is also presented.

INTRODUCTION AND HISTORICAL BACKGROUND

The current French design method for airfield flexible pavement is implemented in the DCA software distributed by the Civil Aviation Technical Center (STAC). The design procedure is described in ICAO Aerodrome Design Manual [1].

The previous US flexible design method is described in the ICAO Aerodrome Design Manual [1] and in FAA Advisory Circular (AC) 150/5320-6D [2].

Both methods are based on the CBR (California Bearing Ratio) approach initially developed by the US Army Corps of Engineers (USACE). The major pavement failure mode is assumed to consist of surface rutting caused by shear failure of the subgrade. The design procedure consists in increasing pavement thickness to protect the subgrade.

The design curves are drawn specifically for each aircraft and the output data is the total thickness of the pavement above the layer to be protected. In US charts, data inputs include the subgrade CBR, the annual departures and the aircraft gross weight. The relationship between loads and the number of allowable coverages is based on full-scale traffic tests to failure conducted by USACE during the period from 1940 through the early 1970s. In French charts, data input includes subgrade CBR and the so-called "allowable load," i.e, the load that is presumed to cause subgrade failure when applied 10,000 times. Equivalency between loads and the number of coverages is based on plate load tests performed in the 1950's by Aéroports de Paris at Orly Airport.

The deficiencies of the CBR method are largely recognized today. For example, the equivalent thickness concept is not easily adaptable to alternative construction practices and new or innovative materials (e.g., high performance materials, reclaimed materials, cement treated capping layers, etc.) or to ageing and seasonal effects. Furthermore, the CBR-based design curves for flexible pavements in AC 150/5320-6D were developed using the ESWL (equivalent single-wheel load) concept for multiple-wheel gears. The ESWL is defined as the load on a single tire that produces the same maximum vertical deflection at subgrade level as the multiple wheel load. For the ESWL calculation, the pavement structure is assumed to be a uniform elastic half-space (Boussinesq model). The pavement damage indicator is the maximum vertical deflection at the top of the subgrade. In general, the number of wheels used to compute ESWL is the number that yields the maximum value for ESWL. For example, the curves for the Boeing B747, with four main gears consisting of four wheels each, were developed based on all 16 wheels, since this grouping produces the maximum ESWL. Full-scale pavement tests to failure showed that the deflection-based design procedure overpredicted the ESWL corresponding to multi-wheel landing gears. This led to the introduction of pavement thickness reduction factors, such as alpha (α) factors, modifying the relationship between pavement thickness and design coverages for multiple-wheel aircrafts. These factors did not depend upon the wheel group configurations, or on the arrangement of wheels within an assembly, or on pavement thickness. This revised methodology has been used in practice for many years. However, this procedure was shown to overstate the damaging effect of multi-wheel landing gears (in particular, the 6-wheel bogie of the Boeing B777 and the complex landing gear of the Airbus 380 which consists of 4- and 6-wheel bogies).

Although it may have been possible to adjust the CBR method to address new gear configurations and increased pavement loading [3], a gradual transition has taken place worldwide over the last years, moving to rational design concepts using mechanisticly driven performance models and layered elastic procedures. This change has been also encouraged by the advent of more and more powerful computers, considerably reducing execution times.

In France at the end of the 1990's, the STAC and the Laboratoire Central des Ponts et Chaussées (LCPC) launched a research program designed to develop a new method for the structural design of airfield pavements. This new design method is based on the application of the French rational design method. The released software is *Alizé*-Airfield pavement, built from the *Alizé* software originally developed in the 1980's by the LCPC for the design of road pavements [4][5]. *Alizé*-Airfield pavement is not yet fully operational for design applications but is already useful for research and as an expert analysis tool. *Alizé*-Airfield pavement is expected to supersede the CBR-based DCA software as the standard design procedure in France.

In the US, the FAA has introduced a series of computer programs: LEDFAA pavement thickness design procedure in 1995 as FAA Advisory Circular (AC) 150/5320-16, BAKFAA in 2002 (back-calculation of elastic properties using layered elastic analysis) and most recently FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layered Design) in 2006. FAARFIELD became the FAA standard design procedure in September 2009 and is part of AC 150/5320-6E [6].

MAIN FEATURES OF THE RATIONAL US AND FRENCH PROCEDURES

Mechanistic-empirical approach

Pavement performance involves a large number of interacting variables that are often difficult to quantify: variability in material types and material properties (effect of temperature and moisture content, compaction), workmanship, ageing (hardening/rutting/loss of texture), traffic volume, complex gear configurations, tire pressures, etc. The design process, aimed at providing accurate predictions of pavement life, is therefore too complex to be modeled on a purely mechanical level. Pavement life cannot be supposed to depend on one simplistic mechanical indicator (e.g., maximum subgrade deflection or maximum subgrade strain). Therefore, rational procedures used are not purely mechanistic. The need for a calibration phase between theoretical computations and on-site results explains the development of a mechanistic-empirical approach.

Indoor full-scale tests conducted from 1999 through the present at the National Airport Pavement Test Facility (NAPTF) at Atlantic City International Airport, New Jersey, USA and outdoor full-scale tests (PEP – A380 Pavement Experimental Program [7] performed from 1998 to 2001 by AIRBUS (Toulouse-Blagnac airport, France) contributed significantly to the development of a wide experimental data base.

Aim of the rational design procedure

The rational design methods used in both the US and France consist in verifying that a pre-designed flexible structure can support mechanically over a particular subgrade a given level of traffic accumulated over a specified lifetime (20 years in the US and 10 years in France). This verification is carried out by comparing:

- maximum strains developed in the various pavement materials, which are calculated using the multi-layer linear elastic model, and
- allowable strains for each material, which are determined from the fatigue characteristics resulting from experimental data.

In the US method, the latter come from accelerated traffic tests on specially-built structures. In the French method, experimental data are derived from laboratory tests (for bound materials) and empirical failure relationships (for unbound materials and subgrade).The structure is considered to be properly designed if the computed strain values are less than or equal to the allowable strain values.

Since the damage due to repeated loading is assumed to be caused by fatigue in bound materials and permanent deformation in unbound layers and subgrade, the relevant failure criteria are:

- tensile strains at the bottom of asphalt layers (the surface layer in FAARFIELD and the asphalt base layer in *Alizé*-Airfield pavement),

- vertical compressive strains at the top of the subgrade (in FAARFIELD) and at the top of the subgrade and the unbound granular materials (UGM) in *Alizé*-Airfield pavement.

MAIN IMPROVEMENTS OF THE RATIONAL METHOD OVER THE CBR METHOD

Traffic mix

In the previous FAA design procedure based on the CBR method, the traffic mixture is expressed in terms of a single design aircraft. All annual departures are converted to equivalent annual departures of this design aircraft. Similarly, in the current version of the French CBR procedure, passes of each aircraft of the traffic mix are converted into equivalent passes of a reference load (allowable load at 10,000 passes). Comparison of the relative effect of each airplane is then possible but the equivalency relation between applied loads and number of allowable coverages remains questionable for multiple-wheeled landing gears.

In the new rational methods, such conversion procedures are no longer necessary; instead, the entire traffic mix is entered. The airplanes are selected from a library of 250 aircraft in *Alizé*-Airfield pavement, and 400 aircraft in FAARFIELD. In *Alizé*-Airfield pavement, a key feature is that the whole geometry of the aircraft is displayed at scale and in interactive mode, giving the user the ability to get information about the gear geometry (radius, weights and contact pressures of all the wheels, distances to the nose gear, longitudinal paths of the wheels). In both programs, the aircraft characteristics as provided by manufacturers are stored in an internal aircraft library and cannot be changed by the user. However, gear configurations may be modified if needed. In FAARFIELD, user-modified or user-created gears may be stored in an external library in Extensible Markup Language (XML) format.

Aircraft wander

In the CBR method as implemented by the FAA, aircraft wander is accounted for by means of the pass-to-coverage ratio (P/C). Since P/C is determined by statistical analysis of gear load distribution at the pavement surface, the reduction in damage due to aircraft wander is the same for all pavement thicknesses. In the French CBR method, the aircraft wander is accounted for by means of a pass-to-coverage ratio fixed at 3.65. Thus, in the French method, the aircraft wander depends on neither the aircraft nor the pavement structure and materials.

By contrast, in the US rational method as exemplified by FAARFIELD, the pass-to-coverage ratio is computed at top of the subgrade (for the subgrade strain criterion). The assumed wander is normally distributed with a standard deviation of 0.775m (30.5 in.). For tandem wheels, the P/C ratio is further adjusted by a factor between 1 and the number of wheels, depending on the depth of the structure above the subgrade.

In the French rational method as implemented in *Alizé*, the pass-to-coverage concept is abandoned. The lateral distribution of traffic is taken into account by combining the individual damage factors created by the aircraft at different transverse distances from a given computation point, using Miner's rule. The designer can specify the standard deviation of wander for each aircraft in the traffic mix. (The default value is set at $2\sigma = 1.5$ m, which is similar to the FAARFIELD value.)

Cumulative Damage Factor (CDF)

Cumulative Damage Factor (CDF) is a basic concept for the rational approach to thickness design. Multiple aircraft types are accounted for by using Miner's rule. The damaging effects of all aircraft are summed in accordance with the law: $CDF = CDF_1 + \dots + CDF_A$, where A is the total number of airplanes in the mix. The thickness design is based on the assumption that failure occurs when the value of CDF reaches 1 for any failure criterion. When CDF < 1, the pavement structural life exceeds the design life, and when CDF > 1, the pavement is expected to fail before the end of the design life. Values of cumulative damage greater than 1 do not necessarily mean that the pavement will no longer support traffic, rather that it meets the definition of failure for the failure mode and the design software under consideration.

In FAARFIELD, the CDF calculation is expressed as:

$$\text{CDF} = \sum_{i=1}^{A} n_i / N_i \tag{1}$$

where n_i is the number of coverages of airplane i over the design life, and N_i is the number of allowable coverages of airplane i for the given failure mode. For subgrade failure of flexible pavements, the values of N_i were derived from full-scale tests where the failure criterion was significant rutting accompanied by 2.5 cm (1 inch) of upheaval expressed at the pavement surface adjacent to the traffic lane [8].

In *Alizé*-Airfield pavement, strains are converted to elementary damage using a performance model of the form:

$$\delta D = \frac{1}{N_i} = \left(\frac{K}{\varepsilon}\right)^b \tag{2}$$

where N_i is the predicted life expressed as repetitions of the load-induced strain ε, K is a material constant, and b the damage exponent of the material.

The cumulative damage is still expressed by Eq. (1), but with n_i the number of repetitions of δD and N_i now defined by Eq. (2).

In the current version of *Alizé*-Airfield pavement, thickness adjustments – and adjustments to material properties if needed - must be made manually such that the cumulative damage is as close as possible to 1 in the final design. By contrast, in FAARFIELD, the iterative procedure to reach the thickness design is automatic.

Failure mode

For flexible pavement design, FAARFIELD and *Alizé* both use the maximum vertical strain at the top of subgrade as the predictor of subgrade shear failure, which in turn is assumed to protect against rutting failure of the complete structure.

In FAARFIELD, the predominant failure mode by default remains the subgrade. However, pavement failure due to fatigue cracking of the asphalt layers is also addressed in both rational methods. In FAARFIELD, computation of the CDF at the bottom of the asphalt surface layer is optional, but recommended as a final design check. In *Alizé*-Airfield pavement, considering that the pavement thickness is increased to accommodate higher loads and greater repetitions, the assumption is made that a considerable proportion of the surface rutting is due to deformations within pavement bound layers. In certain cases, the subgrade damage can be much lower than the asphalt damage. Therefore, computation of the CDF both at the top of subgrade and at the bottom of the base asphalt layer is strongly recommended in the *Alizé*-Airfield pavement software at all stages of the design.

Layered elastic analysis: computed mechanical values

In the CBR method, the number of wheels used to compute ESWL is the number that yields the maximum value for ESWL. By contrast, both the US and French rational methods consider the separate contribution of each wheel in the gear assembly to the combined strain at the top of the subgrade, as computed directly by layered elastic analysis. The structure is idealized as an elastic, multi-layer mass which is linear, homogeneous and isotropic. Each layer is characterized by its thickness, its elastic modulus *E* and its Poisson's ratio. The layers are horizontally infinite and the deepest layer (subgrade layer) is of infinite thickness. This rational approach eliminates both the alpha factor and the need for ESWL calculations. Strains are computed at pre-defined evaluation points within the pavement structure. The *Alizé*-Airfield pavement software computes strain values along vertical profiles, at discrete points defined inside a two-dimensional (2D) uniform horizontal grid whose discretization can be customized (10 cm minimum and by default). For each level of calculation, a quadrilateral mesh of points is defined. The results are presented as longitudinal or transversal profiles or as 2D or 3D surface iso-values. The 2D computation grid is automatically adapted to each airplane under consideration with its wander positions. FAARFIELD also computes strains at predefined evaluation points, but considers a limited locus of points capturing only the maximum response, rather than a regular grid. This leads to faster computation times than *Alizé*-Airfield pavement (since far fewer strains are actually computed for each gear), but does not allow strains to be plotted on a grid.

In the case of four-wheel and six-wheel gears, the multi-peak pavement response is taken into account in the *Alizé*-Airfield pavement software by integrating the damage along the moving wheel axis. Computed mechanical values depend on two parameters: the excitation frequency and the layer interface characterization (whether bonded, unbonded, or partially bonded). Due to the thermo-visco elastic of bituminous materials, the modulus of asphalt materials depends on the frequency of the test load. The standard frequency for current road pavement design is conventionally set at 10Hz. In the *Alizé*-Airfield pavement software, the frequency is automatically computed according to the airplane speed. The latter can be changed manually, with the default value set at 100km/h.

Allowable mechanical values

Figure 1 is the plot of the allowable strains versus the number of coverages at the top of the subgrade in FAARFIELD and *Alizé*-Airfield pavement. In FAARFIELD, the slope of the subgrade failure model is shallower at high coverages than at low coverages. For a given number of coverages, and in the range of typical traffic volumes (10,000 to 100,000 coverages), the allowable vertical strain at the top of the subgrade is greater in *Alizé*-Airfield pavement than in FAARFIELD, thereby implying lower pavement thicknesses in the French designs than in the US ones. It is also the case that in FAARFIELD, allowable strains are independent of subgrade modulus. This is a departure from earlier versions of the FAA procedure (LEDFAA 1.2), in which the allowable strain was explicitly a function of the subgrade modulus [9].

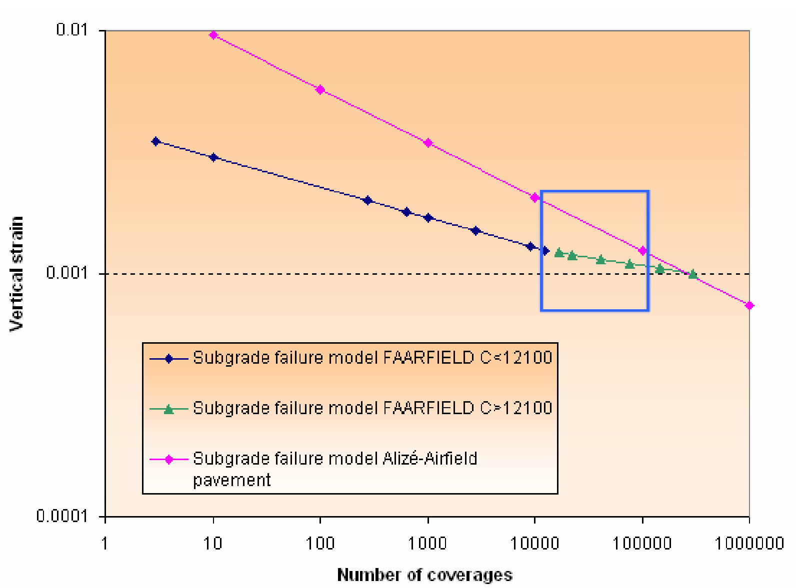

Figure 1. Plot of subgrade failure models in FAARFIELD and *Alizé*-Airfield pavement.

Given that US and French criteria are empirically determined, the resulting designs cannot be directly compared. Each failure criterion is derived from specific environmental and construction conditions. It follows that application of US conditions to the French context, and vice-versa, is not necessarily valid.

In *Alizé*-Airfield pavement, the level of admissible damage is specified by the facility owner, according to the level of service expected for the pavement and is expressed as the risk of failure of the pavement over the whole service life. The effect of the risk parameter on the allowable value is based on a probabilistic approach. This risk factor is a key feature of the French design method that does not appear in the FAA procedure. It takes into account the stochastic nature of the fatigue mechanism in bound material observed both in laboratory and in situ, combined with the variation of the layer thicknesses in real pavements. For example a design failure risk of 5% means that structural failure will affect no more than 5% of the overall length of the pavement before the end of the design life, necessitating structural reinforcement or rebuilding.

In *Alizé*-Airfield pavement, in the case of asphalt materials, the allowable stress or strain value at the base of the layer is a function of:

- the fatigue behaviour of the material expressed by parameters ε_6 (or σ_6) and b, which are the characteristics of the fatigue curve obtained in the laboratory. The asphalt fatigue law includes the asphalt modulus dependency on temperature variations. The standard temperature of 15°C, usually used in French road thickness design, is not suitable for all cases. In the Alize-Airfield pavement software, equivalent temperatures for the asphalt criterion may be calculated automatically for each aircraft included in the traffic mix, according to a statistical histogram representative of the distribution of the aircraft traffic versus the mean temperature in asphalt material over a complete year. The computation of equivalent temperature is performed by elementary computations of the damage due to a reference load for each temperature class, and by using Miner's law.

- the cumulated equivalent traffic (NE) over the service life of the pavement;
- the bearing capacity level of the subgrade soil, through a penalty coefficient for low bearing capacity soils: Ks = 1/1.2 for PF1 (30 to 50MPa) subgrade, Ks = 1/1.1 for PF2 (50 to 120MPa) subgrade, and Ks = 1.0 for PF3 and PF4 (>120MPa) subgrades (where PF1 – PF4 are French designations for subgrade groups based on bearing capacity).
- the risk of failure, as explained above, which is a parameter specified by the facility owner reflecting his management strategy.
- the empirical adjustment of the design model (coefficient Kc) by means of feedback derived from the observation of real pavement behaviour and damage mechanism, and from full scale tests performed with the LCPC Accelerated Pavement Testing Facility [10].

In the case of unbound granular materials (UGM) and subgrade soils, the failure criterion in *Alizé*-Airfield pavement represents the rutting damage due to excessive permanent strains. It does not take into account any risk parameter and the criteria parameters depend neither on the mechanical performance level required by the owner nor on the bearing capacity of the considered material. In this sense, the treatment of subgrade failure in *Alizé* is comparable to FAARFIELD, where the failure strain depends only on the number of coverages.

Material properties

In the CBR design method, the subgrade strength is determined through the CBR test. In rational methods, subgrade modulus can be determined in a number of ways. In FAARFIELD, the preferred procedure in most cases is to use available CBR values. This is because the CBR test is well established in the US, and the flexible failure model (Figure 1) is based on tests on full-scale pavements whose subgrades were characterized using CBR. The equation for converting CBR to subgrade modulus in the FAARFIELD program, originally presented by Heukelom and Klomp [11, 12], is: E = 10.342 CBR (MPa) (E = 15 CBR for E in psi). However, resilient moduli derived from NDT tests (deflection, static or dynamic plate tests) may be also used as input data. In the French methodology, the subgrade failure criteria are derived from laboratory fatigue results rather than from full scale tests. Therefore, in *Alizé*-Airfield pavement, reliability of NDT data is felt to be higher than that of CBR tests and more appropriate to characterize the physical phenomenon involved during the pass of a rolling wheel.

In the CBR design method, the superior load spreading characteristics of bound layers are acknowledged by using granular layer equivalency factors. However, these factors are not related to laboratory-determined mechanical properties of materials. Thus, the French surface asphalt concrete credited with the highest granular equivalency factor (GEF=2.5) displays an intermediate 9,000 MPa modulus value (at 15°C) whereas the French most-performing base asphalt concrete with E = 14,000MPa (at 15°C) is assigned a lower GEF value of 1.9. Besides, input of material mechanical properties in new design methods is necessary to adapt to mechanistic-based specifications for construction (alternative construction practices and materials) and to facilitate further quantitative evaluations for control of long-term structural performance.

Alizé-Airfield pavement deals with nonhomogeneous and stress-dependent responses of UGM by varying the modulus with depth using thin elastic sublayers (< 25 cm). This procedure produces reasonable estimates of deflections measured at selected points in the pavement. Data from falling weight deflectometers (FWD) and from embedded gauges in experimental test structures were used to validate this procedure.

In FAARFIELD, the modulus values of aggregate layers are calculated automatically. As is done in *Alizé*, thick unbound layers are subdivided and a modulus assigned to each sublayer. The modulus of each sublayer is a function of material type (crushed or uncrushed aggregate), layer thickness, and the modulus of the layer below it. The maximum sublayer thicknesses are similar to those in *Alizé* (20.3 cm (8 in.) for uncrushed aggregate and 25.4 cm (10 in.) for crushed aggregate.

MAIN LIMITATIONS OF THE RATIONAL METHOD

The limitations of the isotropic linear elastic theory that underlies the new rational design approach are well known. Long term development is expected to lead towards a more comprehensive design method. This development is mainly linked to:

- the application of advanced models to pavement design, taking into account the thermo-visco elasticity of asphalt layers, the elasto-plastic and nonlinear behavior of UGM, anisotropic layer moduli, dynamic effects, etc.

- the calculation of damage, including: failure mechanisms (proportion of asphalt damage to the total observed damage), limitations of Miner's rule, such as asphalt healing effects, and the special cases of double dual tandem (DDT) and triple dual tandem (TDT) gears, for which the computed cumulative damage should consider the entire stress or strain response signal instead of only the peak tensile strains.

COMPARATIVE SENSITIVITY STUDY

The aim of sensitivity analysis is to quantify the change in output data with respect to the change in input parameters. The sensitivity index, a non-dimensional quantity, is independent of the unit of any variable and enables not only a comparison of the effect of different variables on pavement design within the framework of a given software program but also a comparison between different design programs.

One of the most relevant ouput data in both software programs is the damage computation at the top of the subgrade and at the bottom of asphalt layers (CDF in FAARFIELD and Cumulated

Damages in *Alizé*-Airfield pavement). Following the definition in Garg et al. [13], the sensitivity $S_{x,CDF}$ of the CDF value to any variable x may be approximated in the vicinity of x as:

$$S_{x,CDF} = \frac{CDF_{(x+\Delta x)} - CDF_{(x-\Delta x)}}{2\times\Delta x} \times \frac{x}{CDF_{(x)}} \qquad (3)$$

where x is the value of the variable in question, Δx is taken as 10% of the variable in all cases and $CDF_{(x-\Delta x)}$ and $CDF_{(x+\Delta x)}$ are the values of CDF at $x = x + 10\%$ and $x = x - 10\%$ respectively. A positive value of $S_{x,CDF}$ indicates that the CDF value increases when x increases, implying a decrease in pavement life. A positive sensitivity index value is therefore viewed as a penalizing parameter for design. Conversely, a negative value of $S_{x,CDF}$ indicates that the CDF value decreases when x increases, implying an increase in pavement life and therefore a crediting effect. A high magnitude of positive $S_{x,CDF}$ implies a great loss in pavement performance. A high magnitude of negative $S_{x,CDF}$ corresponds to a great gain in pavement performance.

The sensitivity of CDF value to changes in various parameters has been studied for a nine pavement structures in both programs, as shown in Table 1:

- 3 structures designed for 14600 passes of the A320 aircraft (77.4 tonnes) for three types of subgrade: low strength (CBR 3), medium strength (CBR 8) and high strength (CBR 15).
- 3 structures designed for 14600 passes of the B777-300ER (352.4t) for the three preceding types of subgrade.
- 3 structures designed for a heavy traffic mix consisting of 4 airplanes: A340-600, B777-300ER, A380-800 and B747-200B) for the above types of subgrade.

Table 1.
Traffic Data (Design Life = 20 Years).

Aircraft		No. of Total Passes	Weight, Tonnes
A320		14600	78.4
B777-300ER		14600	352.4
Traffic Mix	A340-600opt	14600	381.2
(4 aircraft)	A380-800F	14600	571.0
	B777-300ER	14600	352.4
	B747-200B	14600	379.2

The sensitivity of CDF to the following input parameters has been studied:

- material properties (subgrade CBR, surface asphalt modulus, base asphalt modulus, base asphalt thickness)
- traffic data (loading, number of passes).

FAARFIELD and *Alizé*-Airfield pavement both provide as output data the CDF at the top of subgrade and at the base of the asphalt layer. In the following summaries, the former is referred to as CDF_{sbg} and the latter to CDF_{asph}. In Table 2, an example of the sensitivity index computation is shown.

Table 2.
Example Computation of $S_{x,CDF}$ in FAARFIELD, Illustrating the Sensitivity of CDF to Variations in the Subgrade CBR Value of ±10%.

	x (CBR)	Δx	$x+\Delta x$	$x-\Delta x$	$CDF_{(x)}$	$CDF_{x+\Delta x}$	$CDF_{x-\Delta x}$	$2\Delta x$	$(CDF_{x+\Delta x} - CDF_{x-\Delta x})2\Delta x$	$S_{x,CDF}$
B777										
	3	0.3	3.3	2.7	1.0	0.57	2.4	0.6	-3.05	-9.15
	8	0.8	8.8	7.2	1.0	0.33	3.22	1.6	-1.80	-14.45
	15	1.5	16.5	13.5	1.0	0.38	2.66	3.0	-0.76	-11.40
A320										
	3	0.3	3.3	2.7	1.0	0.42	1.74	0.6	-2.20	-6.6
	8	0.8	8.8	7.2	1.0	0.47	1.73	1.6	-0.78	-6.3
	15	1.5	16.5	13.5	1.0	0.51	1.75	3.0	-0.41	-6.2
Traffic Mix – 4 Airplanes										
	3	0.3	3.3	2.7	1.0	0.36	2.77	0.6	-4.01	-12.05
	8	0.8	8.8	7.2	1.0	0.34	3.31	1.6	-1.85	-14.85
	15	1.5	16.5	13.5	1.0	0.39	2.80	3.0	-0.80	-12.05

Total pavement thicknesses

Tables 3 to 5 summarize the structures designed by FAARFIELD (version 1.302) and *Alizé*-Airfield pavement (version 4.1.0). Layer moduli for *Alizé*-Airfield pavement are given in MPa, at 15°C. Moduli for FAARFIELD designs are independent of temperature, but the built-in HMA moduli are considered representative of 32°C (90°F). Two designs are presented in *Alizé*-Airfield pavement, one leading to a CDF value at top of subgrade of 1 (or close to 1) and the second one giving a CDF value of 1 (or close to 1) at base of the asphalt layer.

Comparing the total pavement thicknesses using the CDF_{sbg} criterion, it is noted that thicknesses are higher in FAARFIELD than in *Alizé*-Airfield pavement for CBR=8 and CBR=15 subgrades, but the thicknesses for CBR=3 are very close. This result is consistent with the allowable vertical strains at the top of the subgrade as presented in Figure 1.

In the French rational method it is recommended that the designer check that the CDF value at the bottom of the asphalt base layer is close to 1. Comparing the total pavement thicknesses provided by FAARFIELD using the CDF_{sbg} criterion and *Alizé*-Airfield pavement using the CDF_{asph} criterion, it is noted that resulting thicknesses are comparable within 12% for 8 of the 9 designs performed. The exception is the 39% deviation between *Alizé*-Airfield pavement and FAARFIELD for CBR=8 in the B777 case.

Table 3.
Structures designed by *Alizé*-Airfield pavement and FAARFIELD for A320[a].

	A320 – CBR 3		A320 – CBR 8		A320 – CBR 15	
Software	Layer	*E*, MPa	Layer	*E*, MPa	Layer	*E*, MPa
Alizé (CDF_{sbg} criterion)	8 cm HMA surf.	5400	8 cm HMA surf.	5400	6 cm HMA surf.	5400
	9 cm HMA base	9300	9 cm HMA base	9300	7 cm HMA base	9300
	25 cm UGM	187.5	14 cm UGM	200	7 cm UGM	375
	50 cm UGM	75	-	-	-	-
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	92 cm		31 cm		20 cm	
Alizé (CDF_{asph} criterion)	8 cm HMA surf.	5400	8 cm HMA surf.	5400	6 cm HMA surf.	5400
	20 cm HMA base	9300	17 cm HMA base	9300	13 cm HMA base	9300
	24 cm UGM	187.5	24 cm UGM	200	17 cm UGM	375
	50 cm UGM	75	-	-	-	-
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	102 cm		49 cm		36 cm	
FAARFIELD (CDF_{sbg} criterion)	10 cm HMA surf.	1379	10 cm HMA surf.	1379	10 cm HMA surf.	1379
	20 cm HMA base	2758	20 cm HMA base	2758	13 cm HMA base	2758
	63 cm UGA (P-209)	299	23 cm UGA (P-209)	238	18 cm UGA (P-209)	338
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	93 cm		53 cm		41 cm	

[a]14,600 passes at 77.4 tonnes gross weight

Table 4.
Structures designed by *Alizé*-Airfield pavement and FAARFIELD for B777-300ER[a].

	B777 – CBR 3		B777 – CBR 8		B777 – CBR 15	
Software	Layer	*E*, MPa	Layer	*E*, MPa	Layer	*E*, MPa
Alizé (CDF_{sbg} criterion)	8 cm HMA surf.	5400	8 cm HMA surf.	5400	9 cm HMA surf.	5400
	26 cm HMA base	9300	13 cm HMA base	9300	9 cm HMA base	9300
	26 cm UGM	400	19 cm UGM	400	14 cm UGM	375
	26 cm UGM	187.5	19 cm UGM	200	-	-
	80 cm UGM	75	-	-	-	-
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	166 cm		59 cm		32 cm	
Alizé (CDF_{asph} criterion)	8 cm HMA surf.	5400	8 cm HMA surf.	5400	9 cm HMA surf.	5400
	24 cm HMA base	9300	20 cm HMA base	9300	15 cm HMA base	9300
	27 cm UGM	400	17 cm UGM	400	27 cm UGM	375
	27 cm UGM	187.5	17 cm UGM	200	-	-
	80 cm UGM	75	-	-	-	-
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	166 cm		62 cm		51 cm	
FAARFIELD (CDF_{sbg} criterion)	10 cm HMA surf.	1379	10 cm HMA surf.	1379	10 cm HMA surf.	1379
	28 cm HMA base	2758	28 cm HMA base	2758	14 cm HMA base	2758
	124 cm UGA (P-209)	487	48 cm UGA (P-209)	355	32 cm UGA (P-209)	360
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	162 cm		86 cm		56 cm	

[a]14,600 passes at 352.4 tonnes gross weight

Table 5.
Structures designed by *Alizé*-Airfield pavement and FAARFIELD for Heavy Aircraft Mix[a].

	Traffic Mix – CBR 3		Traffic Mix – CBR 8		Traffic Mix – CBR 15	
Software	Layer	*E*, MPa	Layer	*E*, MPa	Layer	*E*, MPa
Alizé (CDF_{sbg} criterion)	8 cm HMA surf.	5400	8 cm HMA surf.	5400	8 cm HMA surf.	5400
	36 cm HMA base	9300	16 cm HMA base	9300	15 cm HMA base	9300
	26 cm UGM	400	26 cm UGM	400	10 cm UGM	375
	26 cm UGM	187.5	26 cm UGM	200	-	-
	80 cm UGM	75	-	-	-	-
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	176 cm		76 cm		33 cm	
Alizé (CDF_{asph} criterion)	8 cm HMA surf.	5400	8 cm HMA surf.	5400	8 cm HMA surf.	5400
	36 cm HMA base	9300	26 cm HMA base	9300	23 cm HMA base	9300
	24 cm UGM	400	25 cm UGM	400	24 cm UGM	375
	24 cm UGM	187.5	25 cm UGM	200	-	-
	80 cm UGM	75	-	-	-	-
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	172 cm		84 cm		55 cm	
FAARFIELD (CDF_{sbg} criterion)	10 cm HMA surf.	1379	10 cm HMA surf.	1379	10 cm HMA surf.	1379
	30 cm HMA base	2758	30 cm HMA base	2758	15 cm HMA base	2758
	130 cm UGA (P-209)	493	45 cm UGA (P-209)	347	34 cm UGA (P-209)	427
	infinite subgrade	30	infinite subgrade	80	infinite subgrade	150
Total	170 cm		85 cm		59 cm	

[a]see Table 1.

CDF at top of subgrade (CDF_{sbg}): high-sensitivity variables

Figure 2 displays values of sensitivities computed for the subgrade strain criterion CDF_{sbg}. The variables shown in Figure 2 are those giving the highest absolute sensitivities, which may be called the high-sensitivity variables: airplane gross weight, subgrade CBR and HMA base layer thickness. The highest absolute values (up to 15) are encountered in FAARFIELD. By comparison, the highest absolute sensitivity value in *Alizé*-Airfield pavement is 4.6.

In FAARFIELD, the CDF computation at the top of the subgrade is highly sensitive to variations in gross weight. Small increases in gross weight negatively impact the FAARFIELD design. Furthermore, the penalizing effect increases with the gross weight (sensitivity of 10 for A320 and up to 15.7 for B777). The penalizing effect of gross weight decreases with increasing CBR for the A320 case; however, for the B777 case, the maximum penalizing effect is observed for the intermediate CBR 8 value. A similar phenomenon was observed by Garg et al. [13] in their analysis of the LEDFAA 1.3 software under mixed traffic. In that example, it was found that the absolute sensitivity of pavement life to B737 gross weight decreased with increasing CBR, but sensitivity to the A380-800 gross weight was greatest for the CBR 8 case.

For FAARFIELD, the sensitivity index values corresponding to CBR subgrade and base asphalt thickness are negative. Thus, an increase in these variables has the effect of lowering the computed CDF. The magnitude of the “credit” is quantified by the absolute value of S_{xCDF}. The maximum crediting effect of CBR is observed for for the cases of B777 and mixed heavy traffic when CBR = 8. (Again, the same observation applies to the 21-aircraft mix in LEDFAA 1.3

[13].) The "crediting" effect increases with the aircraft gross weight, with $S_{SCI,CDF}$ increasing from approximately -6 for the A320 to betweeen-10 and -15 for B777 and mixed heavy traffic. Finally, CDF_{sbg} in FAARFIELD is sensitive to a 10% variation in the base asphalt thickness, with an increase in the sensitivity of this parameter with increasing CBR values.

In *Alizé*-Airfield pavement, positive sensitivity index values are found when the gross weight variable is analyzed. As with FAARFIELD, this is the one input parameter in this group for which an increase penalizes the CDF. However, the sensitivity to gross weight is less than in FAARFIELD (values range from 3.6 to 4.6) and does not seem to depend on the gross weight applied. However, it is remarkable that the same observation made for FAARFIELD also applies to *Alizé*; i.e., the maximum sensitivity to CBR occurs for the B777 and mixed heavy traffic cases when CBR =8.

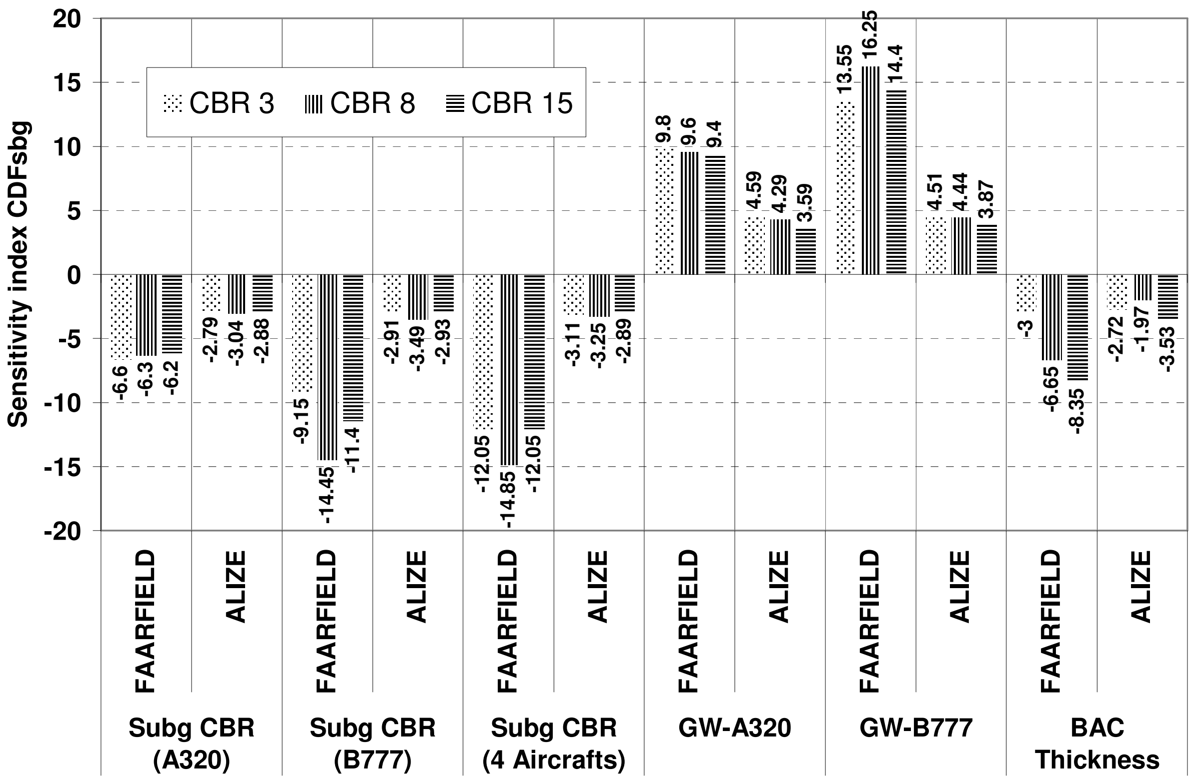

Figure 2. Sensitivity of CDF at top of subgrade to variations in gross weight, base asphalt thickness and subgrade CBR.

To summarize, in *Alizé*-Airfield pavement, all negative sensitivity index values are in the range -3.5 to -1.9. In *Alizé*, an increase in either CBR or HMA base thickness has a less positive effect on the computed CDF than the same increase in FAARFIELD, and the sensitivity to those parameters is also weaker. However, as in FAARFIELD, the sensitivity to CBR in *Alizé*-Airfield pavement is larger for CBR=8 than for CBR=15 for the heaviest aircraft (B777 and heavy traffic mix).

Sensitivity of CDF at top of subgrade: low-sensitivity variables

Relatively low absolute values (<1.75) of the sensitivity index for the subgrade strain CDF criterion are associated both in FAARFIELD and *Alizé*-Airfield pavement with the following variables: surface asphalt modulus, base asphalt modulus and the number of passes of given loads. Therefore, these parameters are not impacting the design significantly.

Figure 3 illustrates the sensitivity of the CDF_{sbg} computation to variations in the above three parameters, for both *Alizé*-Airfield pavement and FAARFIELD and the three load cases shown in Table 1. It is clear from Figure 3 than an increase in surface asphalt modulus has a positive, or crediting effect on the CDF value, corresponding to a negative value of the sensitivity index. is The magnitude of the sensitivity index increases with increasing subgrade CBR, especially in FAARFIELD, where the effect on CDF is greater than in *Alizé*-Airfield pavement. A comparable trend is evidenced for the base asphalt modulus variable.

An increase in the number of passes has a penalizing effect on computed CDF (corresponding to positive values of the sensitivity index) in both software programs. In *Alizé*, this effect is 40% greater for weak subgrades (CBR=3) and high loads. In FAARFIELD, the sensitivity index value is equal to 1 for all load configurations. Variations in CDF computation with respect to variations in the number of passes are independent of the aircraft considered. A 10% decrease in the number of passes produces a 10% loss in CDF value and a 10% increase in the number of passes has the opposite effect. Essentially, this just confirms that there is a linear relationship between passes and accumulated damage, following Miner's law as expressed in Equation (1).

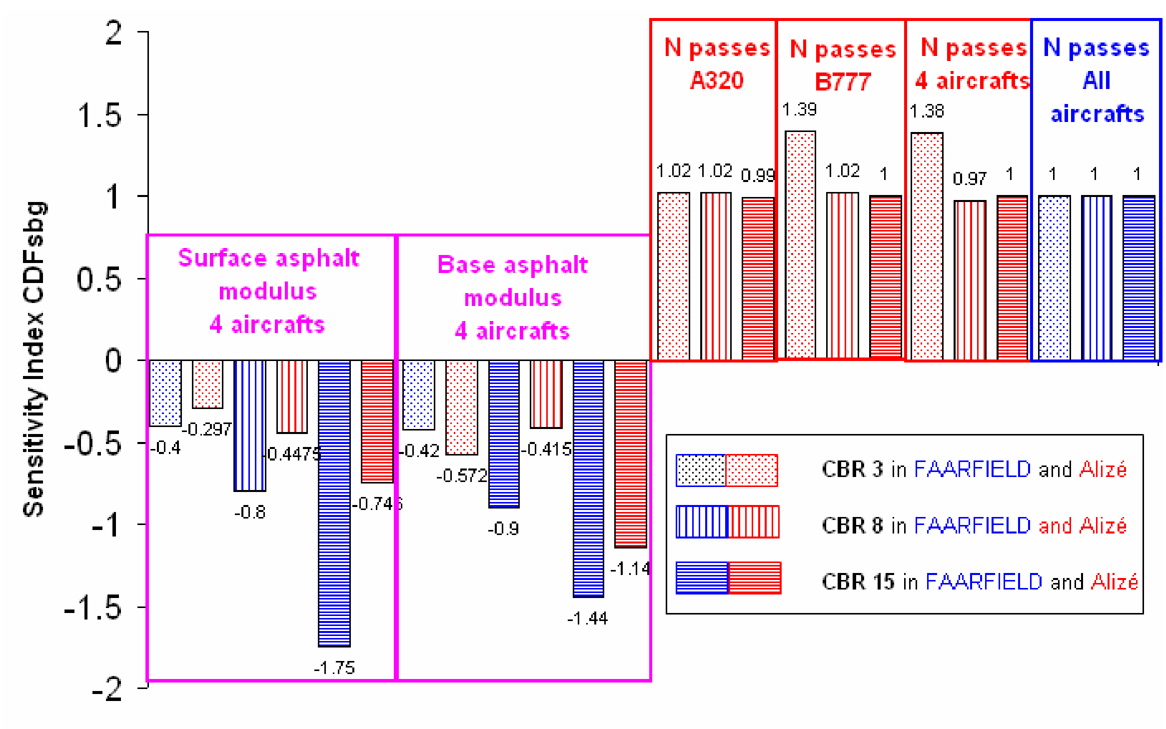

Figure 3. Sensitivity of CDF at top of subgrade to variations in surface asphalt modulus and number of passes.

Sensitivity of CDF at bottom of asphalt layer (CDF_{asph})

Figure 4 illustrates the sensitivity of CDF_{asph} computation to variations of 5 parameters in *Alizé*-Airfield pavement. The sensitivity of the asphalt criterion was studied only in *Alizé*-Airfield pavement, since in contrast to FAARFIELD, this failure criterion is often critical for pavement design in *Alizé*-Airfield pavement.

In *Alizé*-Airfield pavement, the CDF computation at the bottom of the of asphalt layers is highly sensitive to gross weight and asphalt base thickness. An increase in gross weight has a penalizing effect on CDF_{asph}, with positive values of the sensitivity index as large as 4.71. For the A320 aircraft, this penalizing effect decreases with increasing subgrade CBR, following the same trend as observed in Figure 2 for CDF_{sbg}. For the B777, sensitivity to gross aircraft weight is in the 3 - 4 range, with the highest sensitivity index for CBR 8, as in Figure 2. On the other hand, an increase in base asphalt thickness has a beneficial effect on the computed CDF_{asph}, with negative sensitivity indexes ranging from -1.99 to -4.17. In *Alizé*-Airfield pavement, the computed CDF_{asph} is moderately sensitive to the asphalt base modulus. Increases in the asphalt base modulus have a beneficial effect on CDF, with negative sensitivity indexes ranging from -2.05 to -2.66. On the other hand, in *Alizé*-Airfield pavement, the computed value of CDF_{asph} is relatively insensitive to both the subgrade CBR (the opposite of the case with CDF_{sbg}) and the number of passes (similar to CDF_{sbg}).

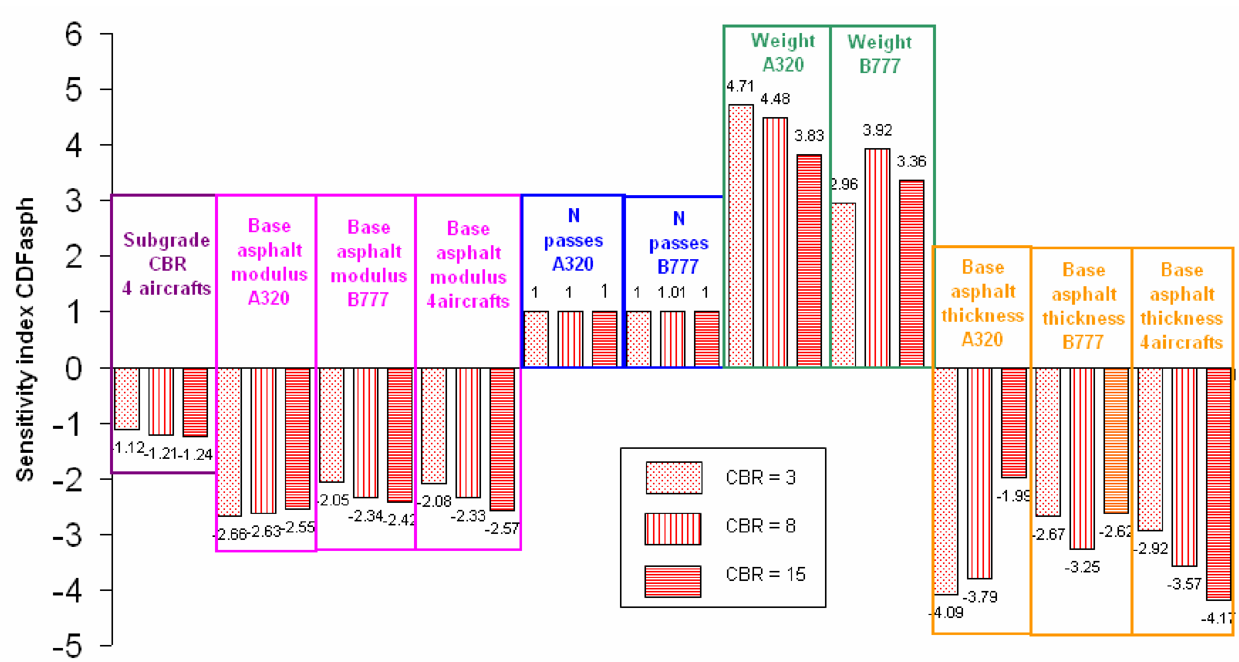

Figure 4. Sensitivity of CDF_{asph} in *Alizé*-Airfield pavement to variations in: subgrade CBR, asphalt base modulus and base thickness, aircraft gross weight, and number of passes.

Discussion

The sensitivity analysis shows that the CDF computed at the top of the subgrade in both FAARFIELD and *Alizé*-Airfield pavement is most sensitive to variations in: gross aircraft weight (first), subgrade CBR (second), and HMA base thickness (third). The sensitivity to those input data is generally higher in FAARFIELD (up to 3.5 times) than in *Alizé*-Airfield pavement. Both programs display certain unexplained trends which were also identified in LEDFAA 1.3 [13]. In particular, sensitivity to a variety of inputs may be highest for medium-strength subgrades (CBR 8) and moderate to high loading conditions. This common trend could be linked to a common way of computation of strains in those programs (i.e., layered elastic analysis).

The sensitivity of CDF_{sbg} in both FAARFIELD and *Alizé*-Airfield pavement to variations in surface and base asphalt modulus, and to variations in the number of passes, is relatively weaker than to the above three variables, with the sensitivity index having values under 1.75. Once again, the sensitivity to those input data is found to be generally higher in FAARFIELD (up to 2.5 times) than in *Alizé*-Airfield pavement.

Insofar as the asphalt criterion is a significant pavement failure indicator in *Alizé*-Airfield pavement, the sensitivity of the CDF computation at the bottom of the asphalt base layer has been examined for this software. The computed value of CDF_{asph} is most sensitive to aircraft gross weight and asphalt base thickness variations. The CDF_{asph} is moderately sensitive to asphalt base modulus variations, and relatively insensitive to subgrade CBR and to the number of passes.

COMPARISON OF COMPUTED MECHANICAL VALUES

A design case study has been chosen for comparison of computed mechanical values derived from FAARFIELD output files and from *Alizé*-Airfield pavement charts. The Service Technique de l'Aviation Civile (STAC) was required to provide a structure adequate to support the expected traffic (Table 6) at Metz-Nancy-Lorraine airport (ETZ) in northeastern France. The structural design from *Alizé*-Airfield pavement necessary to support this traffic mix for the 10-year life standard in French design is given in Table 7.

The same structure has been entered in FAARFIELD. For sake of strict comparison, the identical thickness layer modulus values were entered, using the "undefined layer" function in FAARFIELD rather than the standard FAA layer types (see Figure 5). This avoided issues such as the fixed HMA moduli and minimum base layer thickness requirements in FAARFIELD, that do not necessarily agree with the design in Table 7. A relatively minor discrepancy between the two designs was noted. To enforce the design condition that CDF=1 at the top of the subgrade in FAARFIELD, the base asphalt thickness made slightly higher in FAARFIELD than in *Alizé*-Airfield pavement (19.7 cm rather than 18cm).

Table 6.
Traffic data for Metz-Lorraine-Nancy (ETZ) Airport.

Aircraft	Gross Weight, tonnes	Annual Departures
A300-B4 std	165.9	1825
B747-400	396	1825
B757-200	105	2920
B767-300ER	166	2920
MD11 ER	274	1825
MD11 Belly	274	1825

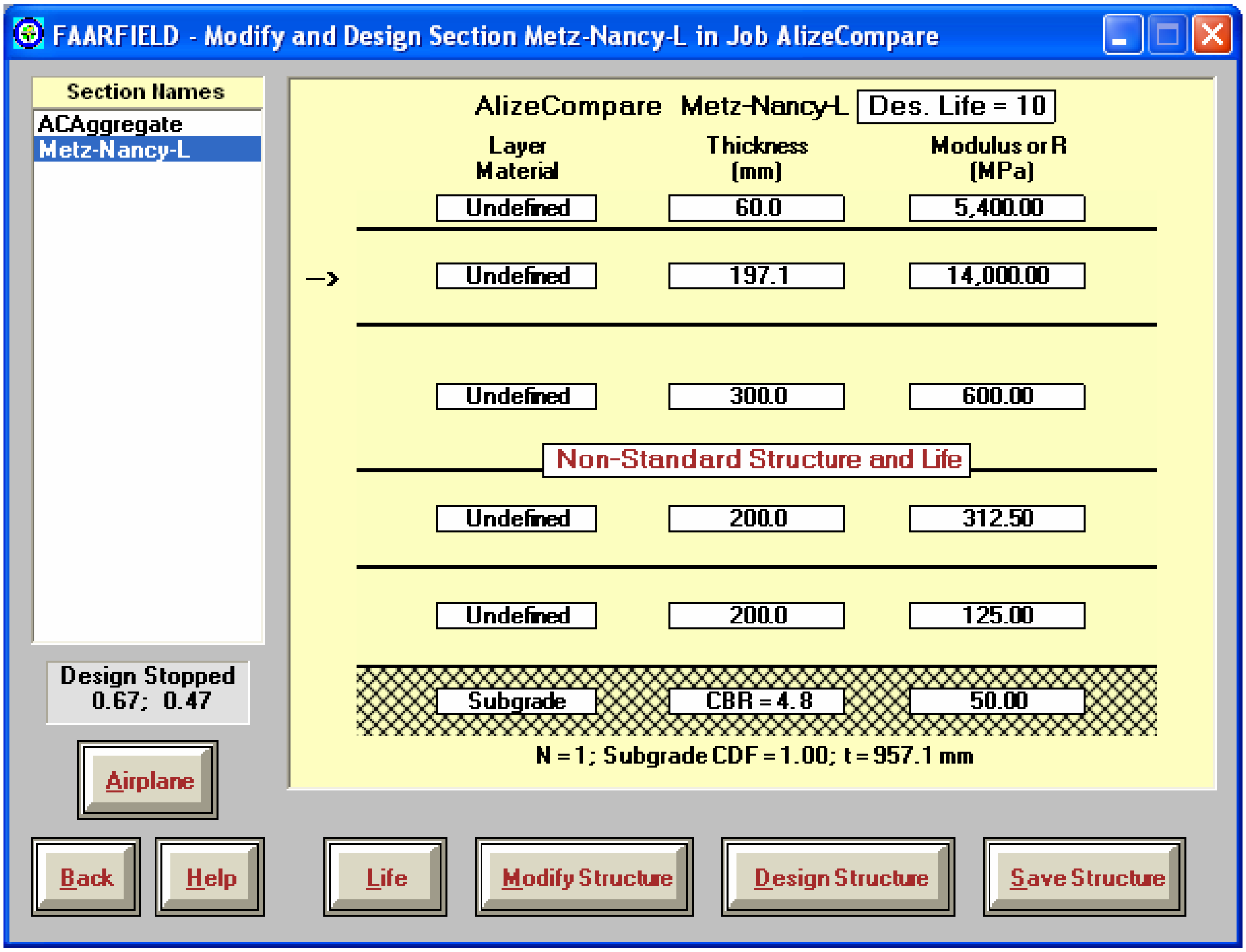

Figure 5. Structure for ETZ traffic mix as defined in FAARFIELD.

Table 7.
Reference Structure.

Layer Type	Thickness, cm	Modulus, MPa
HMA Surface	6.0	5,400
HMA Base	18 .0(*Alizé*) / 19.7 FAARFIELD	14,000
UGM 3	30.0	600
UGM 2	20.0	312.5
UGM 1	20.0	125
Subgrade	infinite	50

Comparison of computed mechanical values at the top of the subgrade

The vertical strain computed at top of subgrade in *Alizé* (Figure 6a) is slightly higher (no more than 3.1%) than the corresponding strain in FAARFIELD (with the exception of the strain computed under the MD11 belly gear). When the thickness of the asphalt layer in *Alizé* is changed to 19.7 cm to agree with the FAARFIELD design, then the discrepancy becomes negligible. The vertical stress computed at top of subgrade in both programs (Figure 6b) is nearly identical (again, except for the belly gear of the ND11).

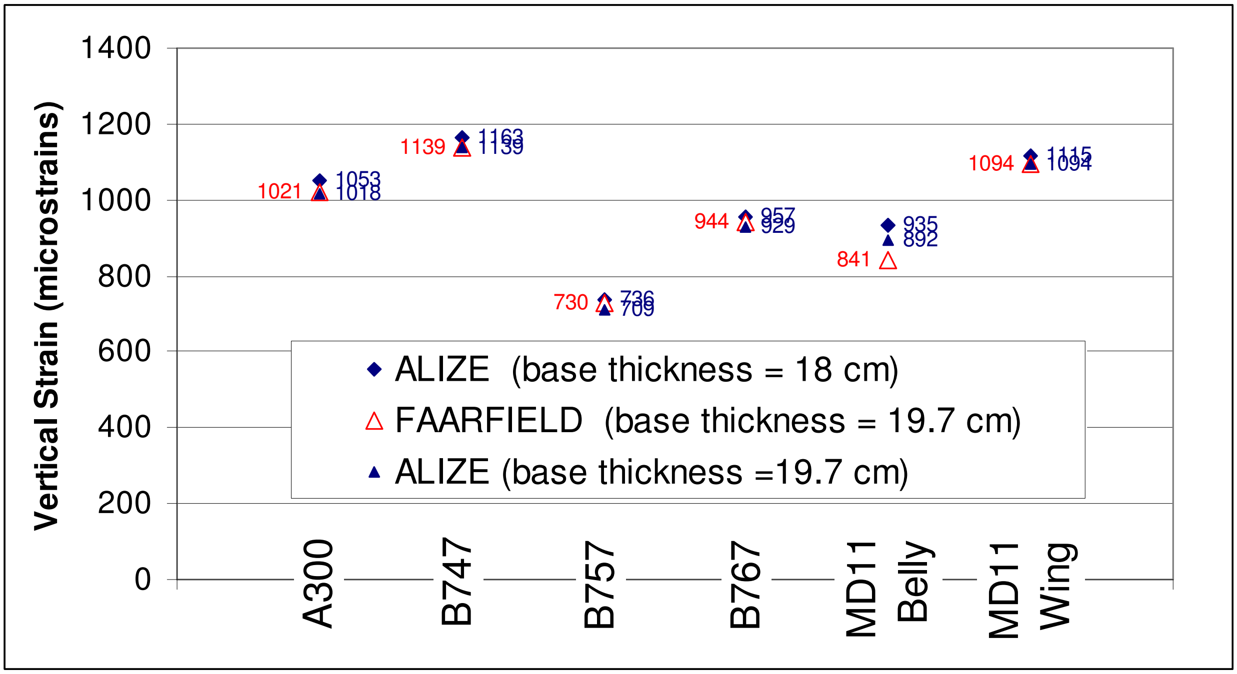

Figure 6(a). Computed vertical strain at top of subgrade.

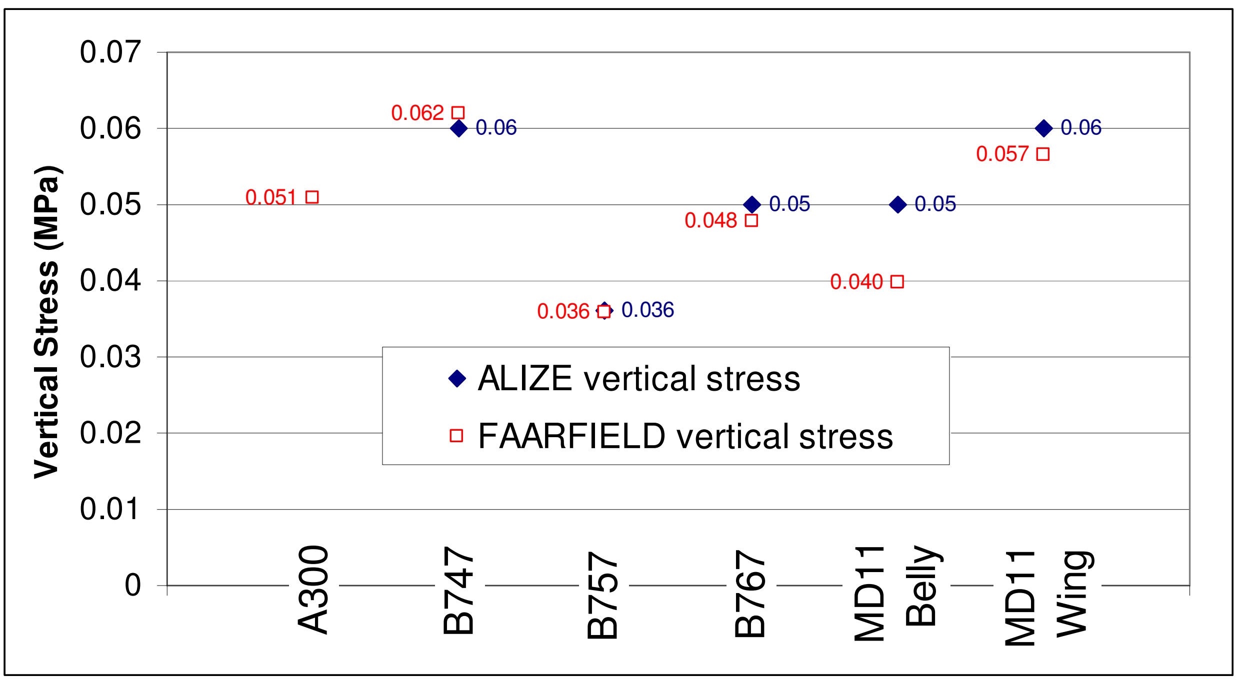

Figure 6(b). Computed vertical stress at top of subgrade.

Comparison of computed mechanical values at the bottom of the asphalt surface layer.

The *x* and *y* components of horizontal strains computed (Figures 7a and 7b) for all aircraft at the bottom of the HMA surface layer are equal or very nearly so in FAA and French design programs (except once again for the belly gear of the MD11).

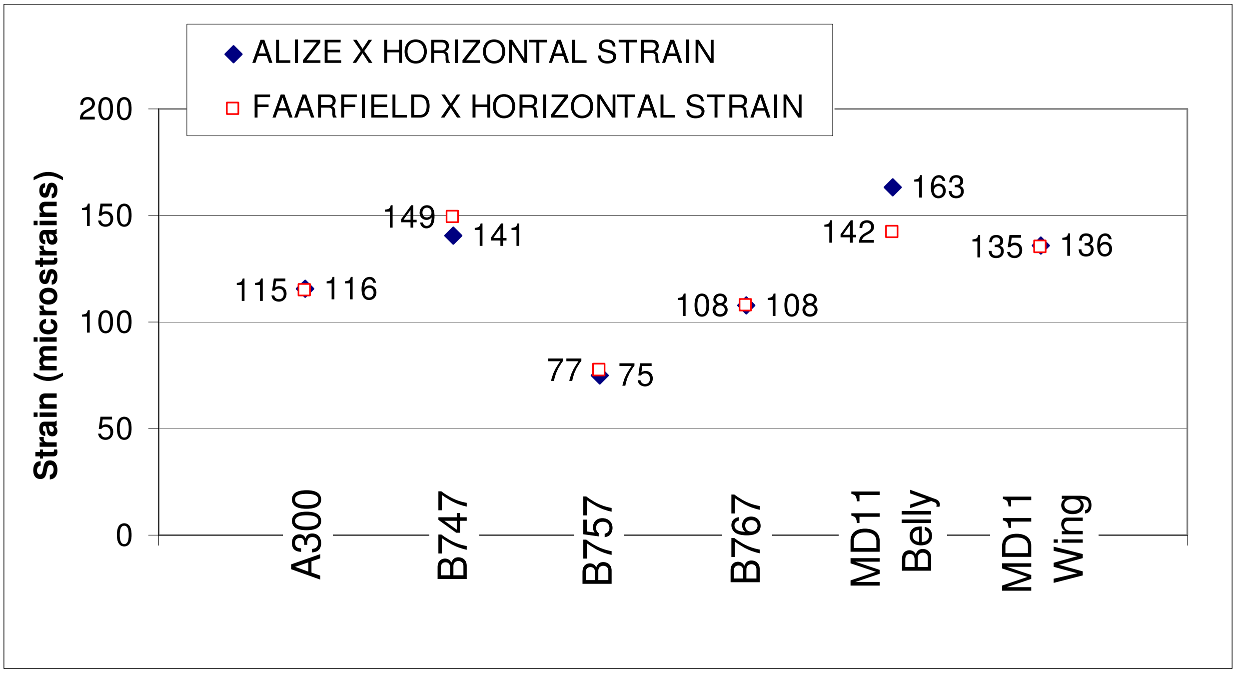

Figure 7(a). Horizontal strain (*x*-direction) at bottom of asphalt surface layer.

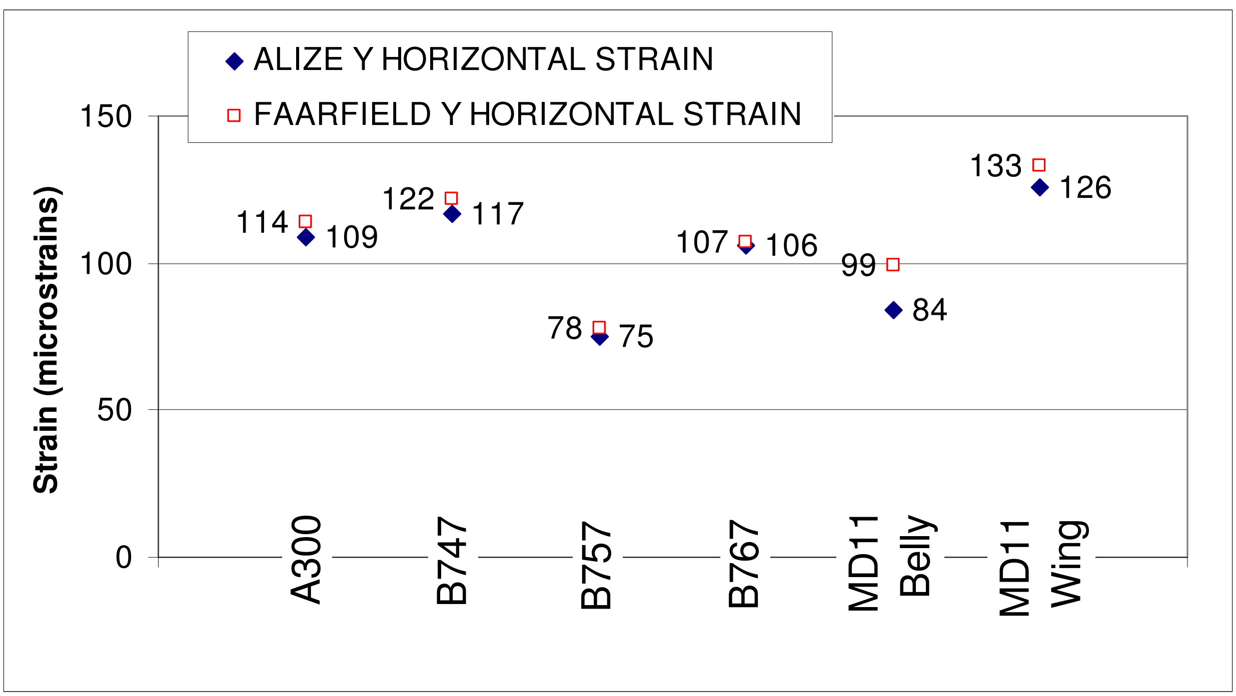

Figure 7(a). Horizontal strain (*y*-direction) at bottom of asphalt surface layer.

CONCLUSION

The CBR pavement design method uses simplified representations of the pavement structure and loading configurations. New rational procedures use mechanistic models to address varying material properties, as well as varying and complex loading conditions. Mechanical indicators are introduced, typically elastic strains at subgrade and asphalt levels. Computed strains from layered elastic analysis are correlated to experimentally determined allowable strains. The French *Alizé*-Airfield pavement and US FAARFIELD procedures share this basic approach to design. The discrepancies observed between the two software programs arise from the determination of the allowable strains and stresses, specifically from the construction of the damage/failure curves for the different layers (subgrade, asphalt surface, base layer, etc.). In the *Alizé*-Airfield pavement program, damage laws are deduced from laboratory tests and adjusted using feedback from road pavements with high coverage levels. The FAA flexible pavement design procedure relies on results of full-scale accelerated traffic tests performed at the FAA's National Airport Pavement Test Facility (NAPTF). Different design philosophies may make direct thickness design comparisons between FAARFIELD and *Alizé*-Airfield pavement problematic even when identical input data are entered. However, computation of mechanical values at critical levels of the designed structures (vertical strain and stress at top of subgrade and *x*- and *y*-components of horizontal strain at the bottom of asphalt layers) is nearly identical in both programs, when similar structural and loading conditions are selected. This result is quite satisfactory and is in accordance with field data (measurement of strains from embedded gauges).

A sensitivity study at the subgrade level demonstrates that both rational design methods are more sensitive to variations in gross weight and in subgrade CBR than in any other input variables. Variations in asphalt thickness and moduli do impact the design, but to a lesser extent. The sensitivity of the design method to the number of aircraft passes is demonstrated to be low and globally independent of gross weights and CBR values in both design methods. Sensitivity of the method to all the variables considered is in most cases higher in FAARFIELD than in *Alizé*-Airfield pavement. This result seems to be linked to the empirically-determined parameters of the subgrade strain-based failure criteria.

DISCLAIMER

The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA. This paper does not constitute a standard, specification, or regulation.

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